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DEFORMATION BEHAVIOR OF THIN LUBRICANT FILMS AT ELEVATED PRESSURE

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INTRODUCTION

Significant progress has been made over the past year toward understanding the mechanisms which control friction in concentrated contact. The coefficient of friction in concentrated contact is still often dealt with as a disposable parameter in numerical analyses. Boundary and elastohydrodynamic lubrication have been recognized as separate regimes of concentrated contact lubrication since the EHD solution of Ertel-Grubin. However, the delineation of these regimes is nearly always in practice based on the magnitude of the film thickness relative to surface roughness rather than a transition in friction.

It has been observed in boundary lubrication and in some aspects of elastohydrodynamic lubrication that friction is nearly Coulombic in nature - the friction coefficient is only weakly dependent upon load and sliding velocity. In some instances the friction coefficient may be so similar in the boundary and EHD regimes that friction alone does not clearly discriminate the transition from one to the other. These attributes of liquid lubrication would seem enigmatic. However, observation of slip planes (shear bands) within a pressurized liquid film suggest that a liquid lubricant possesses a "material internal friction coefficient" which is a material property of the lubricant and represents the ratio of shear stress to compressive normal stress at which slip

within the film is incipient. The friction coefficient of the contact is then a consequence of and quantitatively related to the lubricant material internal friction coefficient.

The Mohr-Coulomb failure criterion was introduced as a predictive method for slip. Mohr-Coulomb defines two possible orientations for stress induced shear bands. Both are experimentally observed in a high-pressure flow visualization cell and the measure of the included angle between the types of bands is consistent with theory. The concept of a first normal stress difference (once the subject of much speculation in lubricated contact studies) must be introduced to account for the orientation of the shear bands with respect to the principal shear directions.

Much attention has been paid in the literature to the search for a general rheological constitutive equation for liquid lubricants at high pressure. The task is further complicated by the observation of mechanically induced (not be confused with thermal or "adiabatic" shear bands which are simply a solution to the combined energy and momentum equations) shear localization in liquids under combined pressure and shear stress. Constitute behavior by definition excludes localization. It is now apparent that much of the departure from Newtonian behavior which has been attributed to constitutive behavior is actually a result of localization in the form of short-lived shear bands.

Work for the past year is divided into five areas and summarized below.

1. ***Adiabatic Shear Bands***

While investigations into mechanically induced shear localization continue, a very different type of shear band has been observed; apparently for the first time in liquids.

In stress-controlled, high-Brinkman number flow an unstable temperature profile develops near the midplane of the film. This phenomenon has been observed experimentally and modeled numerically. This "adiabatic" shear band becomes strikingly visible because of the strong refractive index gradient. In cooperation with Khonsari at University of Pittsburgh we are analytically investigating thermal instability in rate-controlled shear with a pressure transient. This is more representative of concentrated contact lubrication.

2. *Birefrigence*

Flow birefrigence has been useful for stress analysis in flowing liquids in a manner analogous with photoelasticity in transparent solids. Molecular orientation under stress gives rise to optical aniostropy - the refractive index, n, is different in different directions. We have completed observations of mechanically induced shear bands between crossed polarizers. The analyzer and polarizer were maintained at 90° and together rotated through 180°. No change in fringe pattern was observed. Both white light and a narrow band centered at 605 nm were used. The highest order fringe is located at the entrance to the shear region where the first shear band nucleates. The fringe pattern vanishes as shear band develops. We have extended these measurements to non-viscometric flow.

3. *Theoretical Investigations*

Dr. Y. K. Lee has continued his analytical investigation of mechanical shear localization. To study the evolution of shear banding, we developed a viscoelastic-plastic model and postulate that shear bands will appear when the field equations change from elliptic to

hyperbolic. The model is derived based on a rate formulation and combines the Maxwell fluid model and a compressible plasticity model. The model gives the constitutive relation of a compressible viscoelastic-plastic fluid for which the assumption of Stokes' condition becomes unnecessary. The model accounts for the elastic coupling effect of both the viscous and the rate-independent behavior of a lubricant. The novel feature here is that one can track development of the shear bands rather than try to find them after they are fully established.

We have found that the Mohr-Coulomb failure criterion will predict the orientation of each type of mechanical shear band if the first normal stress difference is approximately equal to the shear stress. A useful feature of this theory is that it accurately describes the variation of critical shear stress with pressure and leads to the concept that friction in lubricated concentrated contacts is a material property of the lubricant related to shear band orientation.

4. *New Equipment Development*

In order to experimentally determine constitutive behavior at higher pressures we recently completed a new concentric cylinder rheometer capable of pressure to 600 MPa. Laser light reflected from a mirrored surface on a torsion bar replaces the usual torque transducer. Results of this instrument complement the shear band observations and aid theoretical modeling.

Two new high-pressure flow visualization cells have been designed and construction has begun. Pressure capabilities of both should exceed 600 MPa.

5. *EHD Traction Modeling*

Results from the new rheometer (described in the previous section) have been used to predict a complete EHD traction curve. Comparison with published traction curves from Johnson at Cambridge show good agreement. Because of the usefulness of this type of modeling we plan to emphasize this aspect over the next year.